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EXPERIMENTAL INVESTIGATION OF DIFFERENT CELLULAR LATTICE STRUCTURES MANUFACTURED BY FUSED DEPOSITION MODELING

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Abstract

Experimental tests were conducted to evaluate the compressive properties (yield strength and compressive modulus) and build time for five different cellular lattice structures fabricated by the Fused Deposition Modeling (FDM) process. The lattice structures had repeating unit cells, and the shapes of the unit cell under study included honeycomb, square, diamond, triangle, and circle. Test specimens were manufactured by a Stratasys Fortus 400mc machine using ABS (Acrylonitrile Butadiene Styrene) as the part material. The five different lattice structures were compared with each other and also with the sparse and sparse-double dense build styles that are directly available from the Fortus machine. Honeycomb structure was found to have the best compression properties for the same porosity, although the differences among the different lattice structures were small (<7%). All of these lattice structures were found to have much higher strength than the specimens with the same porosity built using the sparse and sparse-double dense styles. However, the various lattice structures required significantly longer build times than the sparse and sparse-double dense builds. For the honeycomb structure, our investigation also included the effects of porosity and cell size. Higher porosity led to lower compression strength but shortened build time. For the same porosity, the yield strength could be increased and the build time shortened simultaneously by having a certain cell size.

1. Introduction

The Fused Deposition Modeling (FDM) process is an additive manufacturing (AM) technology that builds a three-dimensional physical part by using a work head to melt a thermoplastic supplied in the form of a wire or filament and to extrude the molten thermoplastic through a small nozzle to deposit the material along a pre-planned path for each cross-section of the CAD model of a three-dimensional part [1,2]. By building a part layer-by-layer, this technology allows for manufacture of parts with complex shapes including internal cellular lattice structures [3], which are very desirable for applications that require lower weight yet with sufficient strength such as in aerospace components [4, 5, 6].

The FDM process is a cost-effective AM process that offers great ease and flexibility in fabricating thermoplastic parts [7, 8]. A previous study showed that the yield strength and stiffness of an FDM part is inversely proportional to porosity [9]. Fang et al. [10] observed that Young's modulus tends to decrease with increase in porosity.

In the present study, five different cellular lattice structures with the same porosity were produced by the FDM process to evaluate the performance of the different lattice structures compared with each other and also with the sparse and sparse-double dense build styles that are readily available from the Fortus machine for fabricating sparse parts. The comparisons were done experimentally and they included compressive properties (yield strength and compressive modulus) and build time. The effects of porosity and cell size were also investigated for the honeycomb structure.

2. Experiment

2.1. Fused Deposition Modeling of Test Parts

The basic materials that can be used by the Fortus machine to build parts include ABS (Acrylonitrile Butadiene Styrene), ULTEM, PC, and PPSF [11-13]. The lattice structures in our study were fabricated with ABS-M30 material, which is 25-70% stronger than standard ABS.

Our FDM process was carried out by Stratasys Fortus 400mc machine. This machine has the accuracy of $\pm .127 \text{ mm} - .0015 \text{ mm}$ per mm and the maximum build dimensions of $406 \times 356 \times 406 \text{ mm}^3$. The layer thickness depends on the exit nozzle diameter, which ranges from 0.330 to 0.127 mm for the Fortus 400mc machine. In our study, the nozzle type was T16 (254 μm in diameter), and the layer thickness was 0.254 mm.

The fabricated test parts were cylindrical with 3.81 cm in diameter and 2.54 cm in height. The shapes of the cellular lattice structures included honeycomb, square, diamond, circle, and triangle, as shown in Fig. 1. Also shown in this figure are parts produced by the Fortus 400mc machine using the sparse and sparse-double dense build styles, in order to compare their performance with the different cellular lattice structures on the compressive properties and build time for test specimens having the same porosity. The sparse parts were built with 5 contours, 45° - 45° raster angle, and 0.020 cm in raster air gap, and the sparse-double dense parts were built with 3 contours, 45° - 45° raster angle, and 0.036 cm in raster air gap.

Since the honeycomb lattice structure was found to have higher compressive strength than the other lattice structures, additional test specimens of the honeycomb structure were built for further compression tests in order to investigate the effects of porosity and cell size on compressive properties and build time. Variations in cell size including edge length and edge width for the test specimens with the honeycomb lattice structure are shown in Fig. 2. Figure 2(a) shows variations in edge length while keeping the edge width constant, thus the porosity increases with increase in edge length. Figure 2(b) shows variations in edge length while having the edge width changed correspondingly to keep the porosity constant.

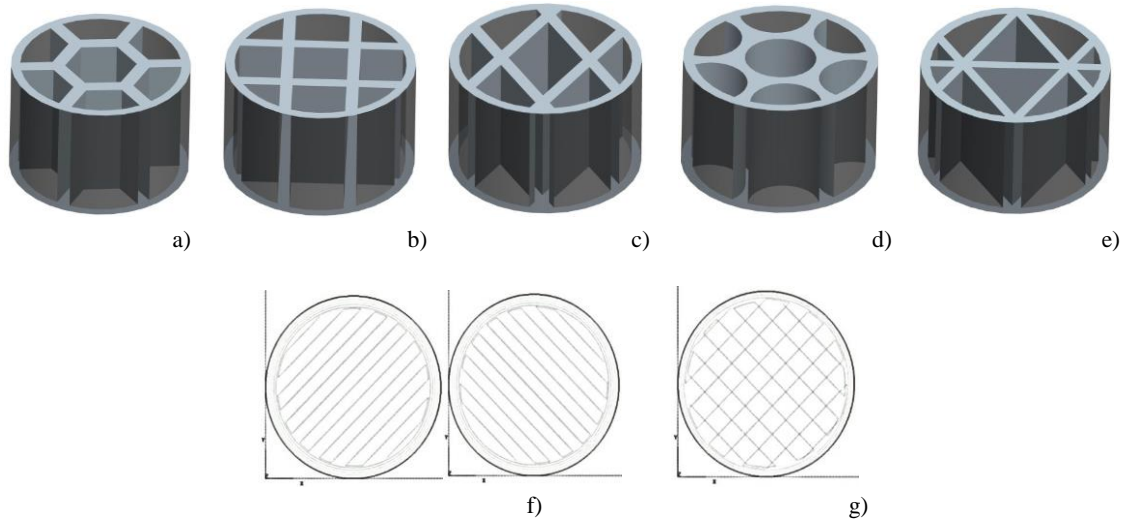


Figure 1. Different cellular lattice structures: a) Honeycomb, b) Square, c) Diamond, d) Circle, and e) Triangle; f) Sparse, g) Sparse-Double Dense.

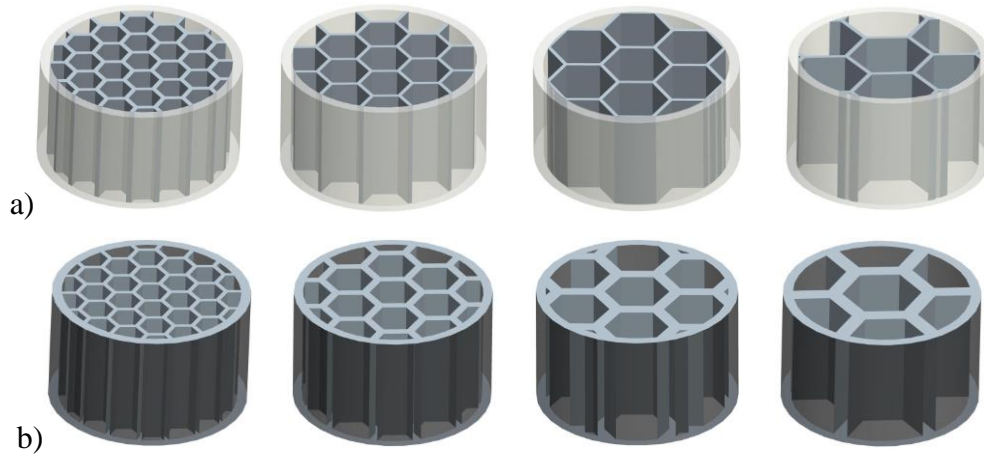


Figure 2. Variations in cell size for the honeycomb lattice structure: a) different edge length and same edge width, and b) varying both edge length and edge width to have the same porosity.

2.2 Compression Tests

Compression tests were performed using an INSTRON 4469 machine, which was equipped with a load cell having its measurement range between -50 and +50 kN. A photo of the experimental apparatus is shown in Fig. 3. The INSTRON machine is controlled by Bluehill 2 software that allows adjustment of the test parameters using a closed-loop digital data acquisition unit.

The speed of 0.51 cm/min was used in the compression test, and the recorded data included yield strength and compressive modulus. The data were collected and averaged over five specimens for each set of parameters.



Figure 3. Photo of the experimental apparatus for the compression tests.

3. Results and Discussion

3.1. Effects of cellular lattice structure

The effects of cellular lattice structure on the compressive properties and build time were compared among the specimens having honeycomb, square, diamond, circle, and triangle lattice structures, as well as those built with the sparse and sparse-double dense build styles available directly from the Fortus machine.

The experimental results obtained were shown in Fig. 4 for the yield strength and in Fig. 5 for the compressive modulus. All of the specimens in these comparisons had the same porosity. The data obtained from the compression tests indicate that the honeycomb cellular lattice structure has the highest yield strength and compressive modulus, and all of the cellular lattice structures have much higher yield strength and compressive modulus than the sparse and sparse-double dense build styles. The yield strength of the honeycomb structure is 217% higher than the sparse-double dense and 253% higher than the sparse build. The compressive modulus of the honeycomb structure is 286% higher than the sparse-double dense build and 579% higher than the sparse build.

The stress-strain curves obtained from the compression tests on the various cellular lattice structures and also the sparse and sparse-double dense builds are shown in Fig. 6. All of the stress-strain curves have similar trends in the elastic region for the various lattice structures. However, the stress-strain curves for the sparse and sparse-double dense builds have somewhat different trends. The maximum strength obtained was between 3.8% and 4.0% for the various lattice structures, 6.8% for the sparse-double dense build, and 24.6% for the sparse build. The parts fabricated using the sparse build appear to be more elastic than those using the sparse-double dense build and those with cellular lattice structures. Figure 7 provides the details of stress-strain curves for the various lattice structures for the range of 3% to 6% strain.

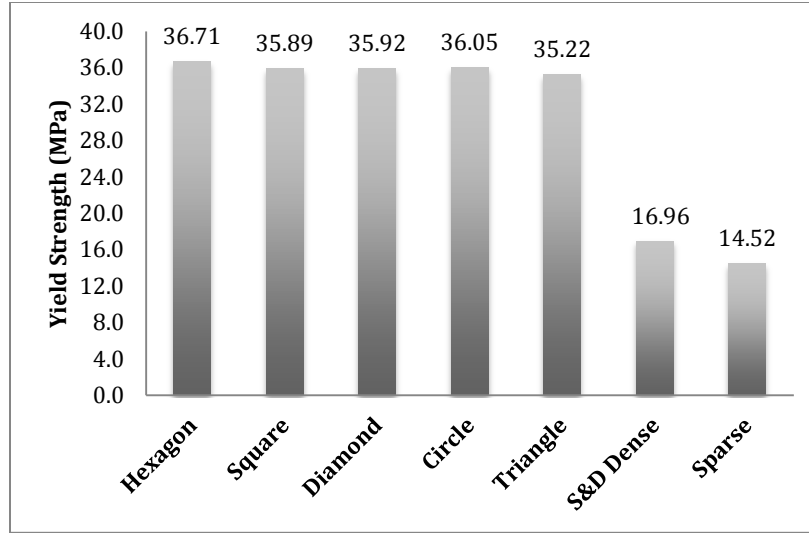


Figure 4. Yield strengths obtained experimentally for different lattice structures and the sparse and sparse-double dense builds at the same porosity.

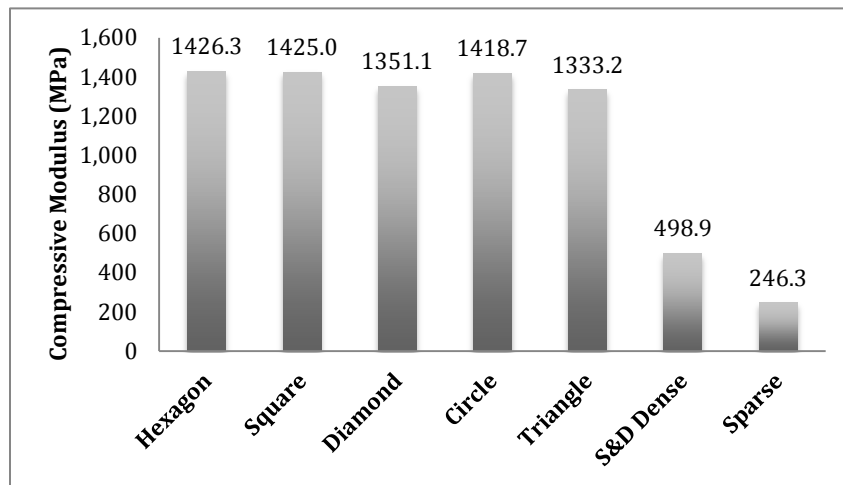


Figure 5. Compressive moduli obtained experimentally for different lattice structures and the sparse and sparse-double dense builds at the same porosity.

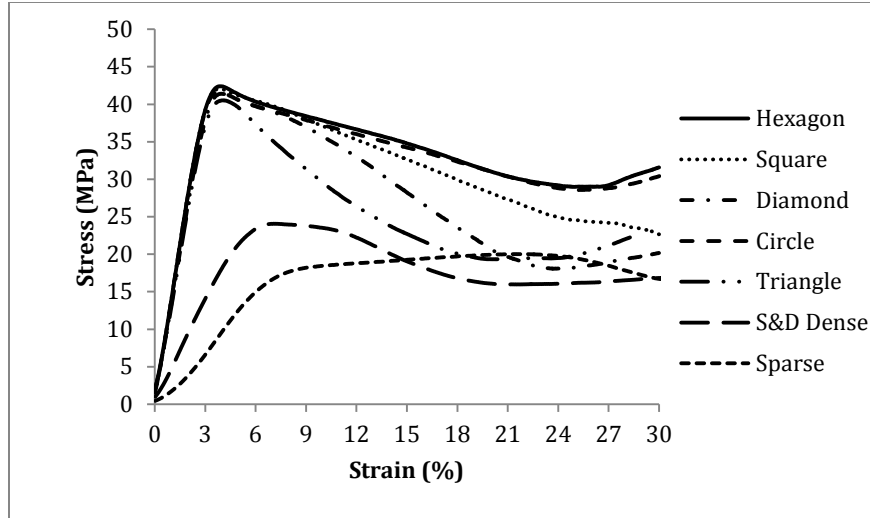


Figure 6. Stress-strain curves for different cellular lattice structures at the same porosity.

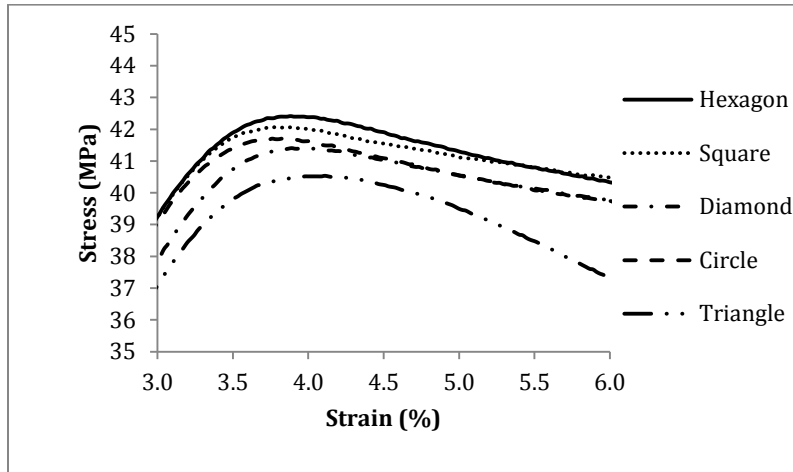


Figure 7. Stress-strain curves in the range of 3% to 6% strain for different cellular lattice structures at the same porosity

The build times for the various cellular lattice structures and the sparse and sparse-double dense builds at the same part porosity are shown in Fig. 8. The build times of the specimens for the various lattice structures ranged between 40 and 47 minutes, while the build times for the sparse and sparse-double dense parts were 20 and 21 minutes, respectively. The build times for the cellular lattice structure were approximately twice as much as the build times for the sparse and sparse-double dense parts.

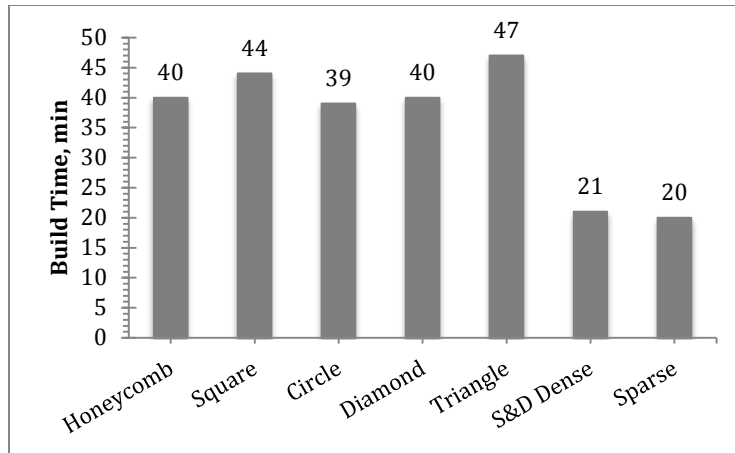


Figure 8. Comparison of build times for different cellular lattice structures and the sparse and the sparse & double dense builds at the same porosity.

3.2. Effects of porosity

Additional test specimens of the honeycomb structure were built to investigate the effects of porosity on compressive properties and build time. Figures 9 and 10 show the changes in the yield strength and compressive modulus, respectively, vs. porosity for the honeycomb cellular lattice structure. The data indicate that both yield strength and compressive modulus decrease with increase in porosity. This expected because increase in part porosity reduces the amount of material in the part. In comparison, the honeycomb structure having 57% in porosity is 36.1% higher in yield strength and 29.6% higher in compressive modulus than the honeycomb structure having 71% in porosity.

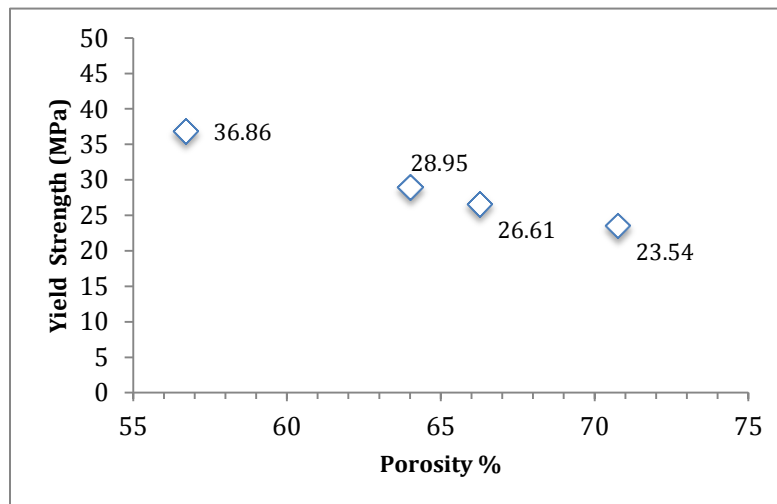


Figure 9. Yield strength vs. porosity for the honeycomb structure

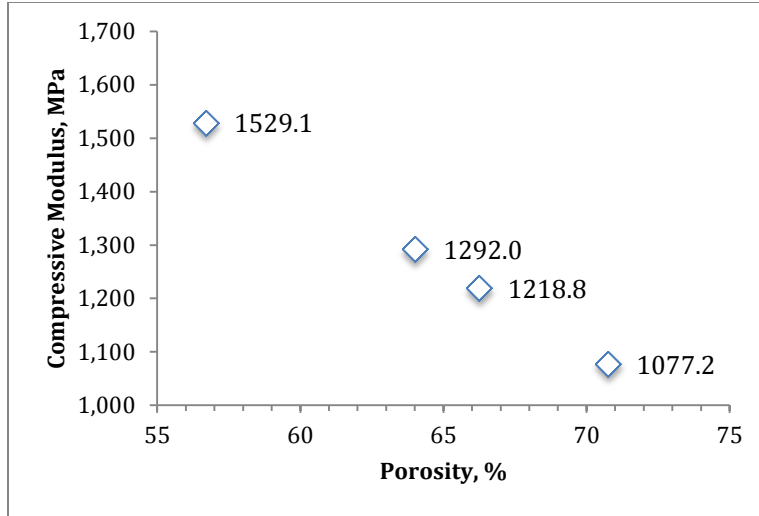


Figure 10. Compressive modulus vs. porosity for the honeycomb structure

The stress-strain curves obtained from the compression tests for the honeycomb specimens with different porosities are shown in Fig. 11. The stress-strain curves all have linear relationships, showing an elastic behavior in the beginning of loading. The maximum strength was obtained at approximately 3.5% strain for all the specimens with different porosities.

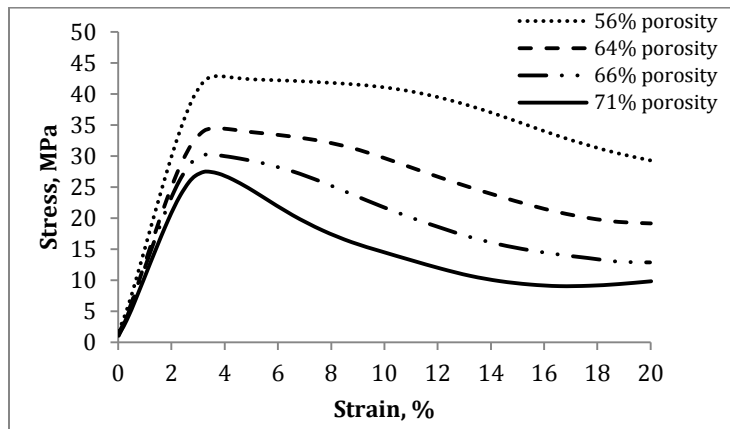


Figure 11. Stress-strain curves for the honeycomb structure at different porosities

The build times for the honeycomb specimens with different porosities are given in Fig. 12, which shows that build time decreases with increase in porosity as expected. The build time of the honeycomb structure having 57% in porosity is 85.3% higher than the honeycomb structure having 71% in porosity.

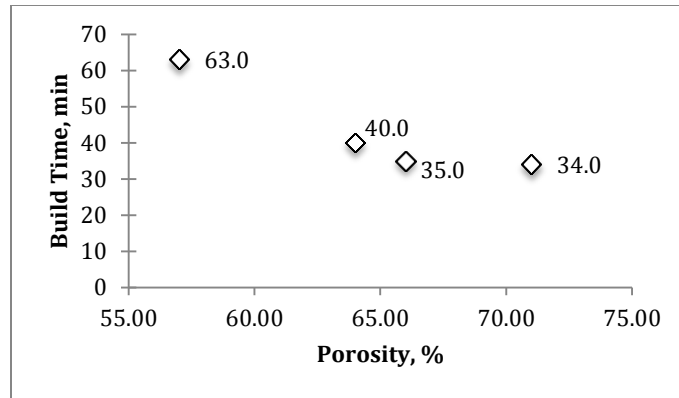


Figure 12. Build time vs. densities for the honeycomb structure at different porosities

3.3. Effects of cell size

Honeycomb specimens having different cell sizes with the edge length ranging from 0.31 cm to 0.76 cm, with the edge width changed correspondingly to keep the same porosity, were fabricated to investigate the effect of cell size on compressive properties and build time. The yield strengths and compressive moduli obtained from the compression tests are shown in Fig. 13 and Fig. 14, respectively. The data indicate that yield strength decreases with increase in edge length between 0.31 cm and 0.61 cm, but then it increases when the edge length increases from 0.61 cm to 0.76 cm. The highest yield strength occurs at 0.76 cm edge length. The compressive modulus obtained from the honeycomb specimens with the various edge lengths are shown in Fig. 14. The compressive modulus decreases with increase in edge length when the edge length increases from 0.31 cm to 0.76 cm.

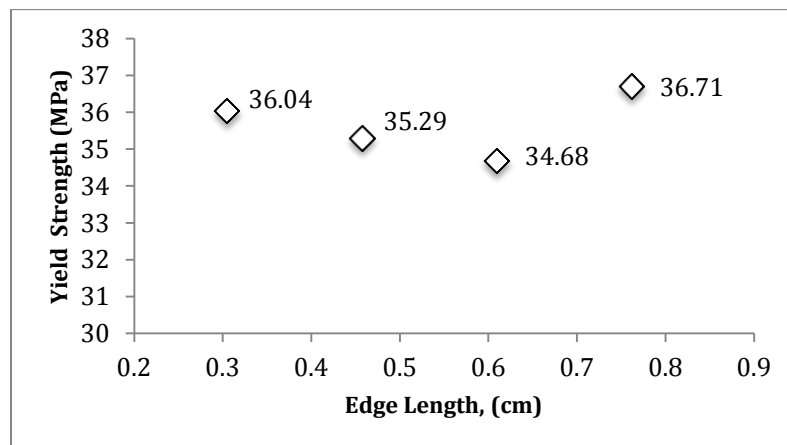


Figure 13. Comparison of yield strength vs. edge length for honeycomb structures with the same porosity.

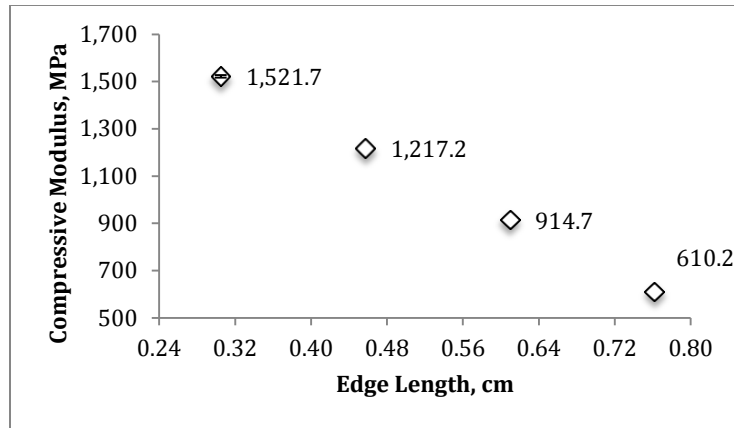


Figure 14. Compressive modulus vs. edge length for honeycomb structures with the same porosity

The stress-strain curves for the honeycomb specimens with varying edge lengths (with the corresponding changes in edge width to keep the same porosity) are shown in Fig. 15. All of the stress-strain curves have similar trends, and the 0.76 cm edge length has the maximum strength at approximately 3.8% strain. Figure 16 provides the stress-strain curves with more details in the range of 3% to 6% strain for the various edge lengths.

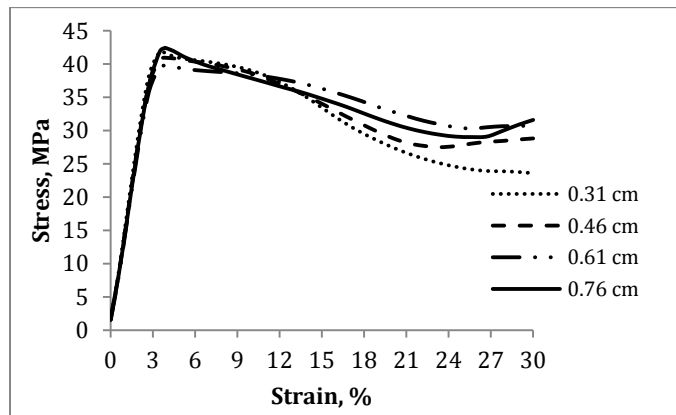


Figure 15. Stress-strain curves for various honeycomb structures with different edge lengths at the same porosity

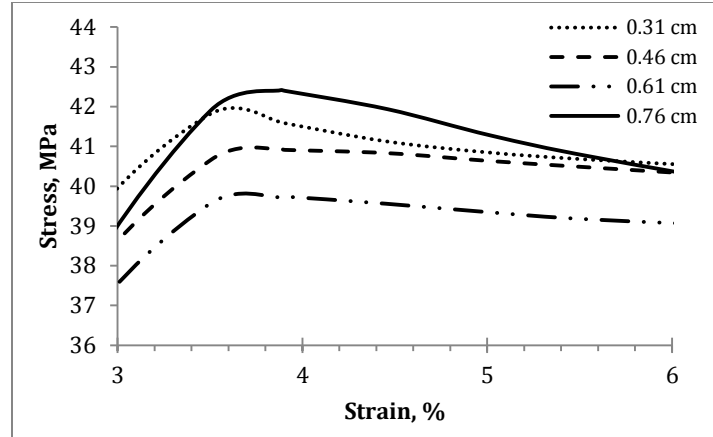


Figure 16. Stress-strain curves in the range of 3% to 6% strain for various honeycomb specimens with different edge lengths at the same porosity

The build times for the various honeycomb specimens that vary in edge length at the same porosity are shown in Fig. 17, which shows that build time decreases with increase in edge length. The build time of the specimen having 0.76 cm in edge length is 36.5% shorter than the specimen having 0.31 cm in edge length. By combining the data in Figs. 15 and 17, we see that among the four different cell sizes (0.31, 0.46, 0.61, and 0.76 cm in edge length) of the honeycomb structure with 57% in porosity, the cell size with 0.76 cm edge length has not only the highest yield strength but also the shortest build time.

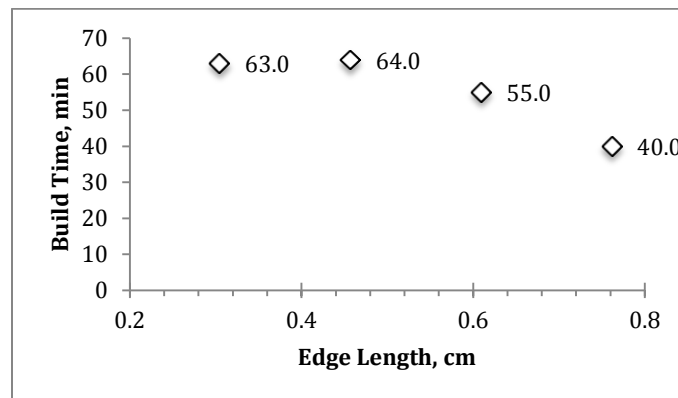


Figure 17. Build time vs. edge length for the honeycomb structure

Conclusions

Experimental studies were conducted to evaluate and compare the compressive properties and build time for periodic lattice structures that have unit cells including honeycomb, square, diamond, circle, and triangle shapes, as well as the sparse and sparse-double dense build styles, fabricated by the fused deposition modeling (FDM) process using Stratasys Fortus 400 machine. The results are summarized below:

- 1) The honeycomb structure has higher yield strength and compressive modulus than the other four lattice structures, and all of the five lattice structures evaluated have much higher yield strength and compressive modulus than the sparse and sparse-double dense build styles. However, the build times of the five lattice structures are approximately twice as much as the build times of the sparse and sparse-double dense builds. Thus, there is a clear trade-off between the cellular lattice structures and the sparse and sparse-double dense builds in terms of compressive properties and build time.
- 2) The compressive properties and build time depend on part porosity for a given lattice structure. The yield strength and compressive modulus decrease and the build time decreases when the part porosity with the honeycomb structure increases. When the porosity of honeycomb specimen increases from 57% to 71% in porosity (~25% increase), correspondingly there is an increase in yield strength by 57%, and a decrease in build time by 46%.
- 3) The compressive properties and build time also depend on the cell size for a given lattice structure with a constant porosity. For the honeycomb structure having the edge length ranging from 0.31 cm to 0.76 cm with the edge width changed correspondingly to keep the same porosity, the yield strength decreases with increase in edge length between 0.31 cm and 0.61 cm but then increases with increase in edge length from 0.61 cm to 0.76 cm. The highest yield strength occurs at 0.76 cm edge length. The compressive modulus decreases continuously when the edge length increases from 0.31 cm to 0.76 cm. The build time decreases with increase in edge length from 0.31 cm to 0.76 cm.

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